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Development of high-power laser ablation process for polycrystalline diamond polishing: Part 3. Processing with an ultra-short pulsed laser up to 1kW

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ABSTRACT

Ultra-short pulse laser machining has been applied to the polishing of polycrystalline diamond (PCD) wafers in order to generate a smooth surface finish and reduce mechanical polishing time. Past studies were first carried out with a 5W laser highlighting the difference in ablation rates between PCD grades and the possible graphitization of diamond on the surface of micrometric PCD grades over a fluence threshold. Some upscaling work was undertaken at 80W with a 3-pulse burst reducing the S_a of a micrometric PCD grade lapped surface by 50% with a volume removal rate double that of the conventional mechanical polishing technique. From these previous base investigations, an ultra-short pulse laser delivering an average power of 1kW at 500fs via state-of-the-art thin disk multi-pass amplification is implemented here to achieve a higher ablation rate for high throughput processing. This is the first time that such an average power is applied on polycrystalline diamond in the ultra-short pulse regime. A burst mode is also implemented which is demonstrated to reduce the S_a by 10% and 55% on fine and coarse grade surfaces respectively compared to single pulse processing. From 80W to 1kW, the ablation rate is increased by a factor of 70 on micrometric PCD grades while the S_a of the initial lapped surface is reduced by 14% without any graphitization of the diamond structure. However, no improvement of the S_a is performed on the initial surface of coarser grades due to the formation of cavities (~5µm wide) potentially caused by the spallation of diamond grains.

Keywords: Ultra-short pulse laser, high-power laser, femtosecond laser, burst mode, laser polishing, polycrystalline diamond, synthetic diamond

1. INTRODUCTION

1.1 Polishing CVD diamond with femtosecond laser

A laser polishing process of PCD material is developed as an alternative to the current mechanical process used in industry as explained in previous papers[1, 2]. Other studies on the laser polishing of PCD are not available in the literature as determined by an extensive literature review. Nevertheless, past studies on the laser polishing of CVD diamond are often present where mostly nanosecond lasers have been utilized because of their high removal rate reaching from a few minutes up to several hours per square centimeter depending on the laser source, the number of processing steps, and the initial roughness[3,4]. The roughness of thin CVD diamond films (< 100µm) with an initial R_a varying between 0.1–1µm can be reduced by a factor between 2 & 4 and higher reductions are achievable for thick films with an R_a varying between 20–30µm. UV femtosecond pulsed lasers have been introduced to overcome the modification of the surface composition observed with nanosecond pulsed lasers[5]. After irradiation with a KrF (λ = 248nm and τ = 500fs) or a Ti:sapphire (λ =

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825nm and τ = 120fs) laser focused with a 100-150µm spot size, no amorphous carbon or graphite are present on both CVD diamond wafers and a natural single diamond crystals type IIA, leading to the conclusion that no phase transformation occurred during ablation with UV femtosecond lasers[5,6,7]. However, UV femtosecond lasers do not produce a surface entirely free of imperfections, as rippled surfaces[8] or streaks[7] can be visible. Even though UV nanosecond lasers have a higher volume removal per unit of time, UV femtosecond lasers reach a higher volume removal per pulse at low fluence (φ_0 < 20J/cm^2)[5,9,10]. So, a higher volume removal per time could theoretically be achieved if the average power of femtosecond lasers could technically match the one delivered by nanosecond lasers. Therefore, after the recent development of high-power femtosecond lasers[11], these results on CVD diamond led to the implementation of a laser polishing process on PCD materials using high-power femtosecond lasers as outlined in this paper.

1.2 Polishing PCD with femtosecond laser delivering an average power $P_{av} \leq$ 80W

Previous studies by the authors on PCD laser polishing started with a 5W average power femtoseconds laser[1] before upscaling up to 80W[2] where various processing parameters have been demonstrated to influence the surface quality of the PCD surface. First, the existence of heat accumulation during ultrashort pulse laser ablation of PCD is demonstrated when the scanning speed is too low and the pulse overlap $po_{\%}$ reaches over a threshold $po_{\%,th}$: when $po_{\%} > po_{\%,th}$, the surface quality is highly deteriorated due to thermal effects, $po_{\%,th}$ = 95% at P_{av} = 5W and $po_{\%,th}$ = 90% at P_{av} = 80W. The number of scanning passes must be limited to a certain number (20 passes as assessed on fine PCD grade), otherwise the surface roughness rises with more passes, like reported by Holder *et al.* on the high-power ultrashort pulse ablation of silicon[12]. For both fine and medium PCD grades, the surface roughness (arithmetical mean height S_a and maximum height S_z) reduces with increasing fluence[2]. As formulated by Eberle, the cobalt binder material present in PCD, is ablated prior to diamond due to its lower fluence threshold compared to diamond[13]. When the ablation of diamond initiates, the surface roughness begins to reduce, and reaches an S_a that is 36% below the initial roughness on a fine PCD grade. The introduction of pulse burst leads to a further reduction of the surface roughness at low fluences per pulse (φ_0 < 9J/cm^2) reaching up to 27% compared to single pulse on fine PCD grades. However, the burst mode exacerbates the heat accumulation effects in the coarser grades which have a higher thermal diffusivity than fine grades, and the surface quality deteriorates compared to single pulse[2].

Kononenko *et al.* can measure the thickness of a graphite layer after processing CVD diamond with ultra-short pulse lasers with a pulse duration down to τ = 100fs[9]. Eberle *et al.* did not observe any graphitization after laser ablating PCD tools (4µm diamond grain size) with a picosecond laser (λ = 1030nm, τ = 10ps)[14] as well as Dold *et al.* (25µm diamond grain size)[15]. However, graphitization of diamond is later demonstrated by the authors to occur in PCD material with ultra-short pulse lasers (λ = 1030nm, τ = 400fs) like observed in CVD diamond[1]. This phase transformation is determined by the fluence and is dependent on the thermal conductivity of the PCD grade. Indeed, an amorphous carbon phase only forms on the surface of a fine PCD grade when φ_0 > 19% (Figure 1, φ_0 is normalized here for confidentiality purposes), whereas no graphitization can be detected on medium and coarse PCD grades as the laser induced heat conducts faster into the bulk of the PCD and the local temperature at the ablated spot remains lower than the graphitization temperature.

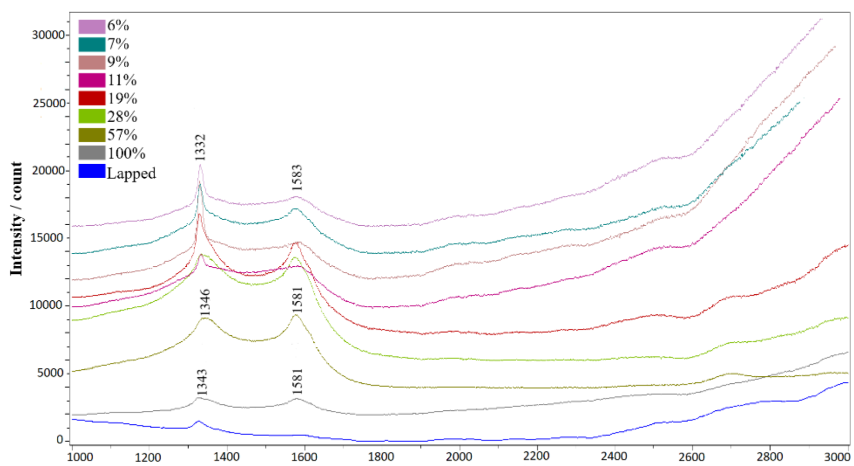

Figure 1. Raman spectra of fine PCD grade surfaces after laser processing at increasing peak fluences φ_0 (λ = 1030nm, τ = 400fs, P_{av} = 5W). The Raman spectrum of the fine PCD grade surface before laser processing is also displayed (lapped surface). The spectra of the

surfaces processed for $\varphi_0 < 11\%$ are similar to the spectrum of the lapped surface with a sharp diamond peak at 1332cm^{-1} and a weak wide peak in the G band at 1583cm^{-1} highlighting the presence of traces of graphite between diamond grain boundaries. When $\varphi_0 = 19\%$ (red curve), the intensity of the peak in the G band at 1583cm^{-1} is becoming sharper and more intense. The diamond peak is no longer centered at 1332cm^{-1} and widens over 1350cm^{-1}, consequences of the appearance of a D peak and its addition to the diamond signal. Both diamond and disordered graphite are present. When $\varphi_0 > 28\%$ (green curve), the diamond peak disappears and, instead, a wide peak D centered at 1346cm^{-1} appears while a G peak is centered at 1580cm^{-1}, characteristic of the presence of amorphous carbon.

With ultra-short pulse lasers, the maximum ablation rate on PCD linearly increases with the average power[1,2] like demonstrated on metals by Neuenschwander *et al.* (Figure 2a)[16]. Furthermore, as displayed in Figure 2b with a 2-pulse burst (red squares), the burst mode appears to increase the ablation rate in comparison to single pulse (black curve) at fluences $\varphi_0 > 3.5$J/cm^2 (more data are required at higher fluence to confirm), while no increase is recorded at lower fluence. As explained by Dold[17], this increase of ablation rate with the burst mode at high fluence is related to heat accumulation which reduces the energy required to reach the vaporization temperature of PCD (diamond/cobalt).

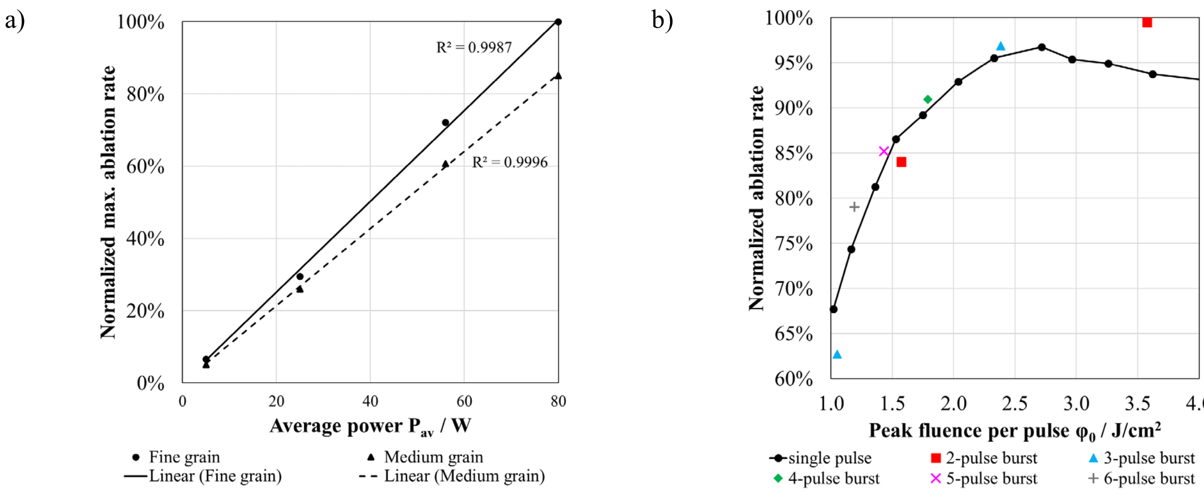

Figure 2. (a) Normalized maximum ablation rate as a function of the average power on fine and medium PCD grades (λ = 1030nm and τ = 400fs). A linear fit is applied on the experimental results for both PCD grades, (b) normalized ablation rate as a function of the peak fluence φ_0 per pulse in a burst for a fine PCD grade, 1 (single pulse) to 6 pulses in a burst are tested (λ = 1030nm, τ = 400fs, P_{av} = 80W, and Δt_B = 23ns)

Finally, a S_a reduction of the initial surface by 50% is achieved with a twice higher removal rate than mechanical polishing on fine PCD grade with a femtosecond laser at P_{av} = 80W (τ = 400fs, 3-pulse burst)[2]. A higher average power ultra-short pulse laser is required in order to further increase the volume removal rate and develop a high throughput process (Figure 2a). The same motivations as Holder *et al.* regarding ultrashort pulse laser milling of silicon led to the development of the process outlined in this article using a 1kW average power femtosecond laser (Table 1)[12].

2. EXPERIMENTAL SET-UP

A development femtosecond laser delivering an average power of 1110W is integrated into the tested laser system. The main characteristics of this laser are summarized in Table 1.

Table 1. Main specifications of the tested laser. Further details regarding the laser specifications are available from Röcker *et al.*[11]

Parameters	**Specifications**
Wavelength	1030nm ± 5nm
Pulse duration	500fs – 800fs
Max. average power*	1110W

Max. frequency	1MHz
Max. pulse energy	2.0mJ at 500kHz
Max. pulses per burst	27
Intra burst distance	22.7ns
Beam quality	TEM_{00}, M^2<1.6
Polarization	Linear

A Lasea station is used to direct the laser beam as illustrated in Figure 3. A galvoscanner deflects the laser beam on the workpiece with a maximum average power of 990W after absorption from the optics. Three PCD grades with different compositions and diamond grain sizes (fine, medium and coarse), as detailed previously[1, 2], are tested for the research presented in this paper. The samples are placed on conventional CNC stages (X, Y, Z) to allow linear movements for successive ablation trials and for positioning of the PCD top surface at the required distance from the focusing optics depending on the targeted spot size. The laser beam is linearly polarized when interacting with the PCD material as no quarter wave plates are set on the optical path due to their optical absorption being too elevated for the prescribed average power. Ultra-short pulse laser ablation with a linear polarizated beam can induce the formation of Laser Induced Periodic Surface Structures (LIPSS)[18,19]. They take the appearance of ripples with a nano structure and periodicity (nanoripples) when processing with a fluence near the ablation threshold[20,21]. They can be observed on CVD diamond surfaces processed with UV and IR femtosecond lasers[8]. Holder *et al.* highlights the presence of LIPPS on silicon wafers processed with the same experimental set up[12]. Nonetheless the formation of LIPSS is not the focus of this paper.

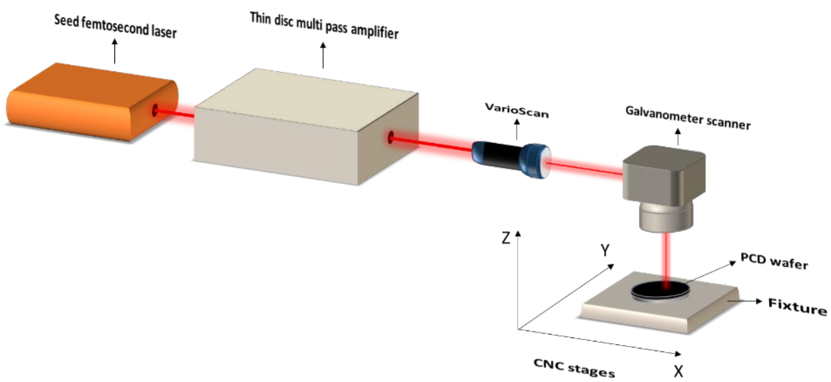

Figure 3. Schematic of the laser system used for laser ablation trials

Surface areas measuring 5mm x 5mm are laser-ablated on the PCD materials. The area roughness parameter S_a is measured over an ablated area of 285µm x 216µm by focus-variation microscopy with an Alicona G4 achieving a resolution of 20nm and a repeatability of 8nm (at mag x50). Five measurements are repeated per sample (four in the corners and one in the middle of the sample) and averaged to minimize the standard deviation up a maximum value of 10% across all trials. Secondary electron images of the ablated surfaces are recorded with a Hitachi S-4800 FEG Scanning Electronic Microscope (SEM). The ablation rate is measured as described previously[1]. The effect of the fluence on the roughness of the ablated surfaces is first investigated by ablating surfaces with different pulse energies. The pulse energy is set by the average power of the laser source (diode efficiency). The final upscaling is done at 2mJ and 1kW.

3. RESULTS

3.1 Study of the effect of the fluence on the surface roughness

As a result of the high average power and the large spot diameter, a wider range of fluence is accessible in comparison to the studies in previously reported studies [1,2]. The peak fluence goes from φ_0 = 0.88J/cm^2 to 50.42J/cm^2 with single pulse (Figure 5a, Figure 6a and Figure 7a). This approach allows more regimes to be distinguished where the S_a reduces for both single pulse and pulse bursts instead of one regime according to previous work[2,13] as discussed in the introduction.

Using fine PCD grade, two fluence ranges of S_a reduction can be distinguished: a first regime where cobalt is ablated/melted only before a second regime where the diamond grains are ablated at higher fluences (Figure 5a). Indeed, during this first regime, clusters of diamond grains are not ablated as visible in Figure 5b and Figure 5d. Then, in the second regime, these clusters are flattened as shown in Figure 5c and Figure 5e. In previous work[2], the trend of the experimental data shows a 5-pulse burst could potentially improve the surface roughness more than a 3-pulse burst. This is confirmed by the results in Figure 5a where the minimum S_a achieved in the second regime is S_a = 59% with a 5-pulse burst. The reduction of S_a values in the second regime with a 5-pulse burst (S_a = 59%) compared to single pulse (S_a = 66%) is confirmed by SEM: the polishing of diamond peaks appears enhanced with a 5-pulse burst in Figure 5e in comparison to single pulse in Figure 5c. The optimal laser ablation of diamond, where the S_a is the lowest in the second regime, is performed at a lower fluence per pulse with a 5-pulse burst (φ_0 = 2.03J/cm^2) than a 3-pulse burst (φ_0 = 3.38J/cm^2) and a single pulse (φ_0 = 7.64J/cm^2) according to Figure 5a. This can be related to incubation effects which causes a reduction of the fluence threshold of diamond with an increased number of pulses in a burst as explained by Metzner *et al.* on the burst ablation of silicon, which is a semiconductor material like diamond[22]. Due to the energy distribution of the pulses (Gaussian here considering the M^2 of the beam), the pulse energy is partially deposited in the material under the form of residual heat where the fluence of the pulse is lower than the fluence threshold of the material. This amount of residual heat is lower in the case of a pulse with less energy and therefore less thermally induced damage is generated. In conclusion, less residual heat is generated when diamond is ablated with a 5-pulse burst explaining the smoother surface roughness achieved.

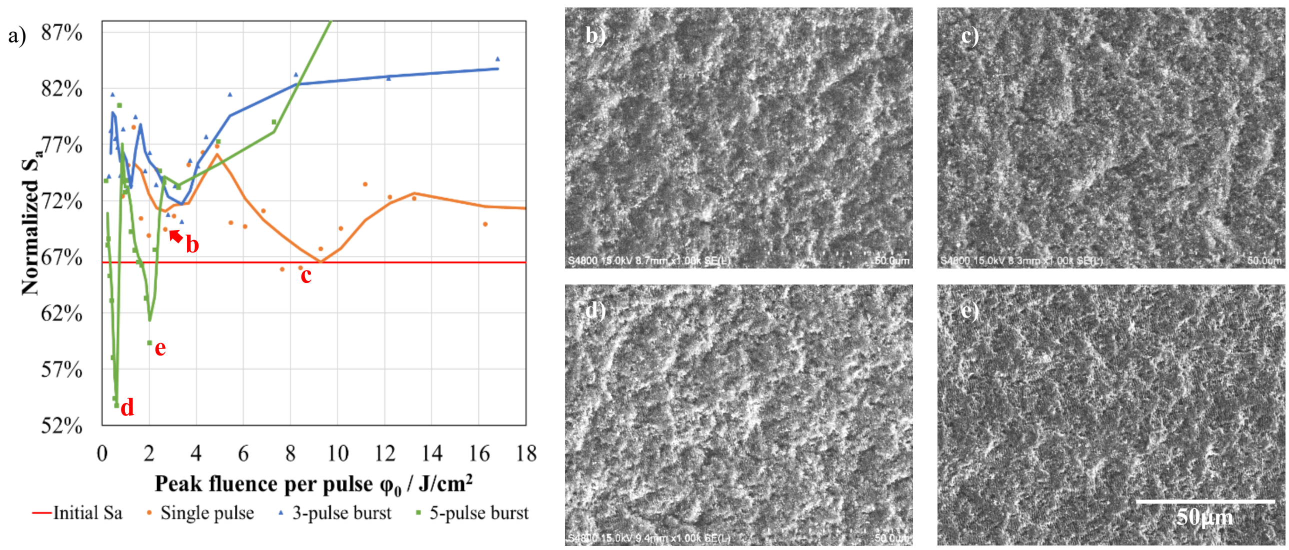

Figure 5. (a) Normalized surface roughness, S_a, of the fine PCD grade surface as a function of the peak fluence per pulse φ_0 for single pulse, 3-pulse burst and 5-pulse burst (λ = 1030nm, τ = 500fs, and 5 scanning passes), and SEM images of the surfaces processed at: (b) single pulse φ_0 = 1.98J/cm^2, (c) single pulse φ_0 = 7.64J/cm^2, (d) 5-pulse burst φ_0 = 0.54J/cm^2, (e) 5-pulse burst φ_0 = 2.03J/cm^2 as highlighted in Figure 5a

On medium PCD grade, three regimes with a S_a reduction can be differentiated at single pulse, 3-pulse, and to a lesser extent 5-pulse (Figure 6a). At single pulse, in comparison previous work[2] where the fluence is limited, two additional regimes can be observed at fluences φ_0 < 9J/cm^2. Similar to the fine grade results in Figure 5, these two regimes correspond to the ablation of cobalt followed by the ablation of diamond. Clusters of diamond are visible in Figure 6b after ablation at φ_0 = 1.98J/cm^2 whereas they are flattened at a higher fluence of φ_0 = 6.85J/cm^2 as shown in Figure 6c. Figure 6c also reveals the formation of cavities on the surface with a size < 5µm. At fluences φ_0 > 9J/cm^2, a third regime is highlighted at single pulse where the surface roughness S_a decreases with increasing fluences until a constant value is reached when φ_0 > 25J/cm^2 as previously observed [2]. The access to higher fluences in this work allows to confirm this observation from 25J/cm^2 to 50J/cm^2. These cavities are more numerous and larger in size ~5µm in this third regime as shown in Figure 6d. These cavities can represent the holes left after diamond grains are expelled off the surface by spallation, mechanism of material removal with ultrashort pulse laser[23-26]. During ultra-short pulse laser ablation, the ultrafast heating (> 10^{14} K/s [27]) and thermalization of the electron/lattice systems (~100ps in the case of aluminum[28]) generate tensile waves within the material. When the tensile strength of the material is exceeded, subsurface voids are formed and grow until fractures are induced parallel to the surface leading to the ejection of layers of material. This spallation mechanism is enhanced in the case of a composite materials like PCD where cobalt and diamond have different thermal expansion coefficients[29]: the variation of volume expansion between the two materials is favorable to the formation and propagation of cracks at the interface diamond/cobalt causing diamond grains to be ejected. An identical behaviour is observed with bursts of pulse with the formation of cavities in a second regime and their enlargement and greater number in a third regime (Figure 6e). The burst mode does not bring any improvement in terms of S_a compared to single pulse (Figure 6a) as proven by the consistency between the smoothest surface topographies achieved in the third regime at single pulse (Figure 6d) and 3-pulse burst (Figure 6e). As observed with the fine grades, the incubation effect with the burst mode are responsible for lowering fluences where the minimum S_a is achieved per regime. However, due to the higher conduction of medium grade over fine grade[30], the heat is spread at a higher rate in the bulk of the medium grade material and less localized around the targeted area which causes less thermal damage. Therefore, the reduction of residual heat with the use of burst mode does not reduce the level of thermal damage in comparison to single pulse. However, the higher conductivity causes stronger heat accumulation and surface damage occurring at $\varphi_0 > 4.07 J/cm^2$ at 3-pulse and responsible for the higher S_a values at 5-pulse burst.

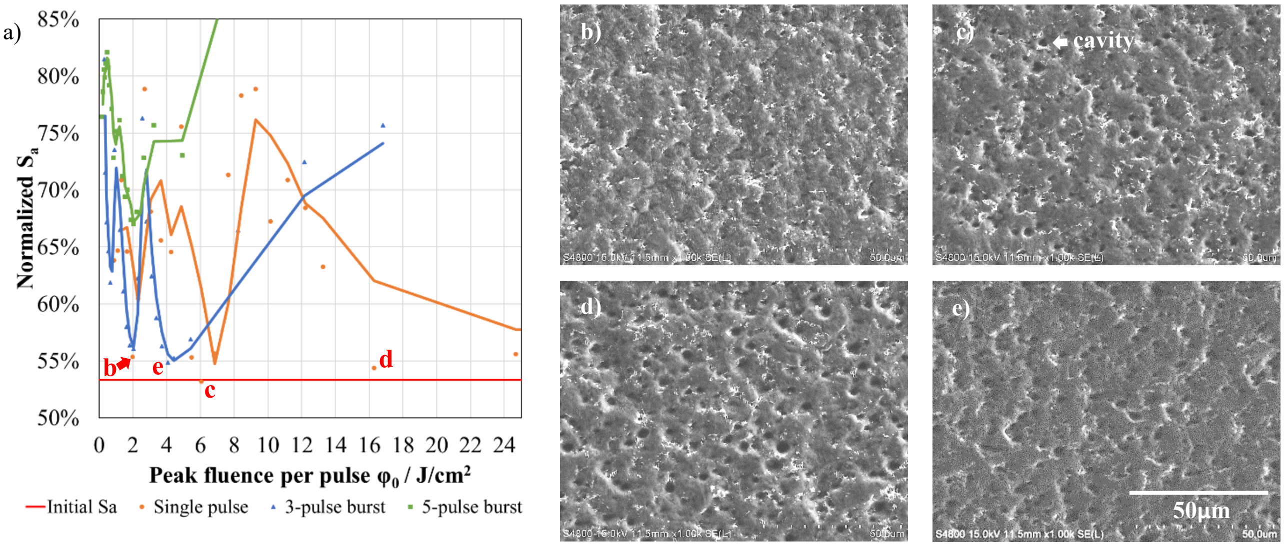

Figure 6. (a) Normalized surface roughness, Sa, of the medium PCD grade surface as a function of the peak fluence per pulse φ_0 for single pulse, 3-pulse burst and 5-pulse burst (λ = 1030nm, τ = 500fs, and 5 scanning passes), and SEM images of the surfaces processed at: (b) single pulse $\varphi_0 = 1.98 J/cm^2$, (c) single pulse $\varphi_0 = 6.85 J/cm^2$, (d) single pulse $\varphi_0 = 16.27 J/cm^2$, (d) 3-pulse burst $\varphi_0 = 4.07 J/cm^2$ as highlighted in Figure 6a

For the coarse PCD grade, two regimes of fluences with a reduction of S_a occurs at single pulse. The number of regimes for 3-pulse and 5-pulse bursts is debatable, nonetheless three regimes are clearly apparent at 7-pulse burst (Figure 7a). At single pulse, ablation of cobalt takes place in the first regime before the ablation of diamond follows in a second, as previously shown for the fine PCD grade. The SEM of the surface processed at $\varphi_0 = 4.27 J/cm^2$ at single pulse shows that diamond grains ~25µm wide, corresponding to the maximum diamond grain size in coarse PCD grade, are not ablated while the area surrounding the grains, corresponding to the location of the binding material, is ablated (Figure 7b). Then, at a higher fluence, ablation of the diamond grains takes place as illustrated by the change of the diamond grains morphology at $\varphi_0 = 9.28 J/cm^2$ in Figure 7c. At 7-pulse burst, diamond grains are ejected leaving cavities with a width < 5µm on the surface in the second regime as highlighted in Figure 7d at $\varphi_0 = 1.09 J/cm^2$. It is consistent with the detection of these cavities by focus variation microscopy in the previous paper[2]. In a third regime, the cavities seem to be more numerous in Figure 7e with the increase of fluence at $\varphi_0 = 1.89 J/cm^2$, and their size remains in the same range < 5µm. Considering the grain size distribution of coarse PCD grades, some diamond grains with a size < 5µm compose the surface and can therefore be expelled during laser ablation as observed earlier with medium PCD grades, while larger grains remain on the surface. As partially determined in a previous study[2], Figure 7a confirms that the addition of pulses per burst reduces the S_a during the ablation of coarse grade surfaces. The SEM analyses corroborates the Sa measurements: a smoother surface is achieved with 7-pulse bursts (Figure 7d) compared to single pulse burst (Figure 7c). Coarser grades have a higher fluence threshold as determined in previous studies[1]. A higher number of pulses per burst allows the reduction of this high fluence threshold via incubation effects and large diamond grains can effectively be ablated at lower fluences with a minimized residual heat. A significant reduction of the Sa can ultimately be achieved in the diamond ablation regime: from $S_a = 42\%$ at single pulse ($\varphi_0 = 9.28 J/cm^2$) to $S_a = 19\%$ at 7-pulse burst ($\varphi_0 = 1.09 J/cm^2$).

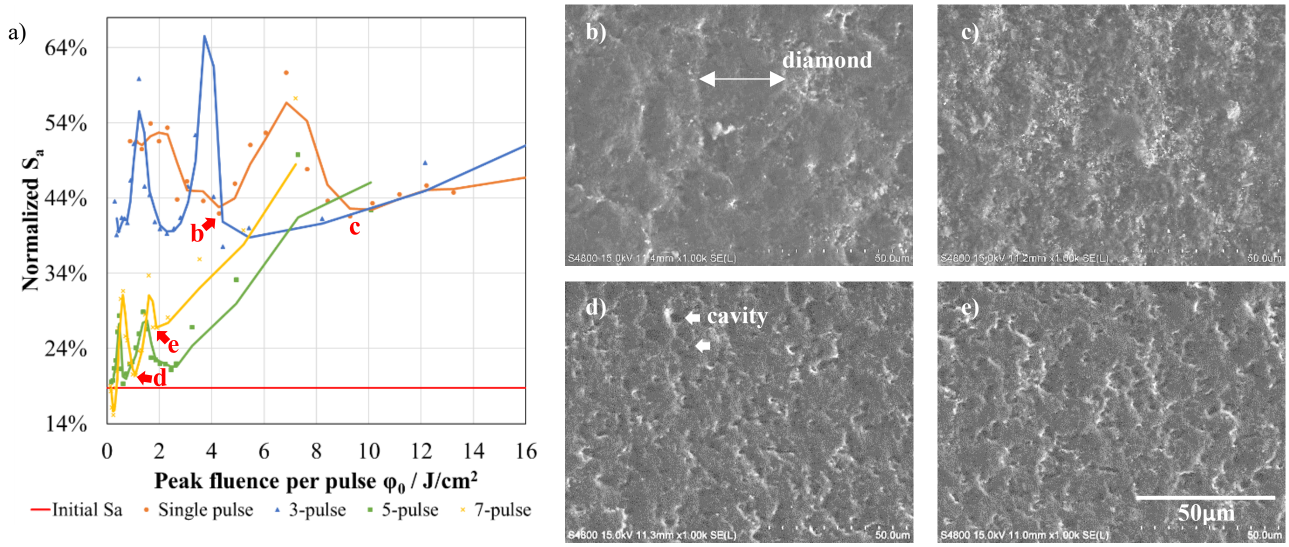

Figure 7. (a) Normalized surface roughness, Sa, of the coarse PCD grade surface as a function of the peak fluence per pulse φ_0 for single pulse, 3-pulse burst and 5-pulse burst ($\lambda = 1030nm$, $\tau = 500fs$, and 5 scanning passes), and SEM images of the surfaces processed at: (b) single pulse $\varphi_0 = 4.27 J/cm^2$, (c) single pulse $\varphi_0 = 9.28 J/cm^2$, (d) 7-pulse burst $\varphi_0 = 1.09 J/cm^2$, (e) 7-pulse burst $\varphi_0 = 1.89 J/cm^2$ as highlighted in Figure 7a

3.2 Process upscaling at $P_{av} = 1kW$

The process is first scaled up to $P_{av} = 260W$ and eventually to $P_{av} = 990W$. This is achieved by defocusing the beam to reach the targeted fluences according to the above surface roughness study (§3.1). The defocusing technique is also employed by Holder *et al.* on the processing of silicon[12]. After optimization of the process parameters, the initial surface roughness S_a of a fine PCD grade can be polished by 14% after laser processing with a 3-pulse burst ($\varphi_0 = 0.88 J/cm^2$ and $P_{av} = 990W$). A 5-pulse burst and processing with a peak fluence per pulse φ_0 in the second regime could potentially improve the surface roughness S_a further (Figure 5a); unfortunately, the S_a measurements were posterior to the upscaling trials which were carried out with a 3-pulse burst following the results from previous studies[2]. The surface topography is represented by SEM in Figure 8d along with the topography of the surfaces processed at lower power, where $P_{av} = 260W$ (Figure 8c) and at single pulse for both $P_{av} = 260W$ (Figure 8a) and $P_{av} = 990W$ (Figure 8b). No significant differences in topography between the surfaces processed at $P_{av} = 260W$ and $P_{av} = 990W$ are noticeable which means the process can successfully be scaled up in terms of average power ramp up. Furthermore, the surfaces appear more homogenous after 3-pulse burst rather than single pulse processing and confirms the reduction of roughness S_a with the burst mode compared to single pulse processing on fine PCD grade surfaces as demonstrated in Figure 5a.

Raman analyses are carried out on these four aforementioned fine grade surfaces to inspect if the diamond structure is still present on the top surface after laser processing at high power (Figure 8e). The spectra are similar to the spectrum taken on a lapped surface pre-laser ablation (Figure 1) with a diamond peak at $1332 cm^{-1}$ as well as a wide G band centered at $1600 cm^{-1}$, and no peak in the D band. Therefore, the occurrence of graphitization can be excluded. This is expected for single pulse processing as the surfaces are processed with a peak fluence $\varphi_0 < 2.65 J/cm^2$ which is lower than the fluence threshold of graphitization as determined in Figure 1. The conclusion in the previously published study[1] regarding the key role of the fluence in the process of diamond graphitization in comparison to the average power is also validated. No additional thermal effects capable of graphitizing the surface arise from the use of a 3-pulse burst (like heat accumulation) at low fluence per pulse, which is consistent with the constant ablation efficiency between single pulse and burst mode processing at $\varphi_0 < 3.5 J/cm^2$ (Figure 2b). The Raman spectrum taken off a surface processed with a 5-pulse burst is also displayed to confirm the presence of diamond and the absence of thermal effects with the burst mode.

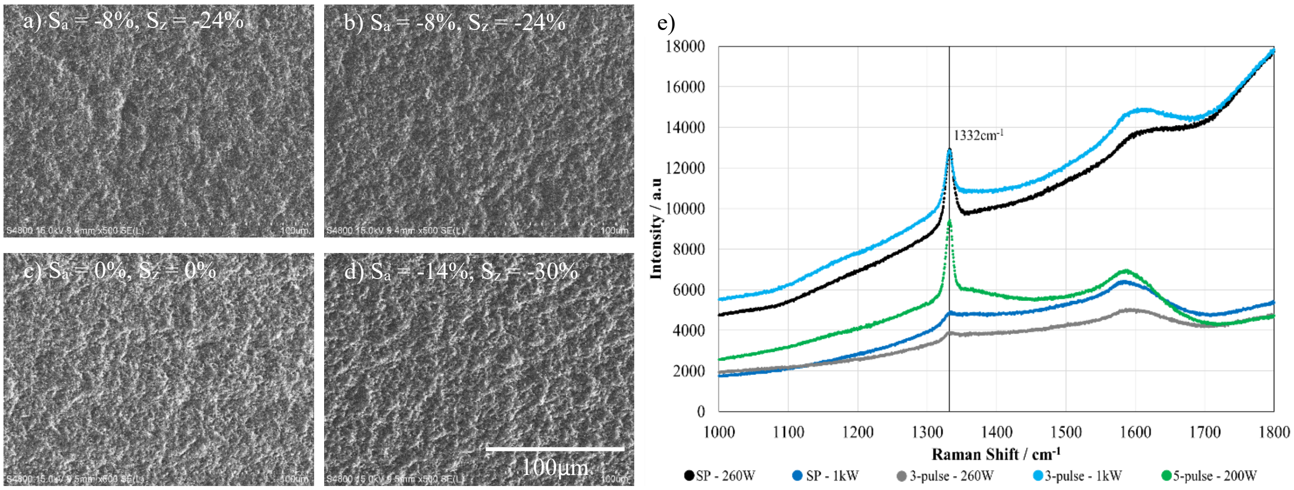

Figure 8. SEM images of fine PCD grade surfaces after laser processing with single pulse at both: (a) P_{av} = 260W, φ_0 = 2.34J/cm^2 and (b) P_{av} = 990W, φ_0 = 2 .65J/cm^2, and with 3-pulse burst at both: (c) P_{av} = 260W, φ_0 = 0.78J/cm^2 and (d) P_{av} = 990W, φ_0 = 0.88J/cm^2 (λ = 1030nm, τ = 500fs, and 25 scanning passes), along with (e) the Raman spectra of these surfaces and the Raman spectrum of the surface processed at 5-pulse φ_0 = 2.03J/cm^2. The S_a and S_z values are relative to the values characterizing the initial surfaces.

This S_a reduction of 14% at P_{av} = 990W (τ = 500fs, 3-pulse burst) is performed with an ablation rate over 70 times higher than at P_{av} = 80W. The increase of ablation rate with the average power from 80W to 260W and further 990W is linear as predicted in Figure 2a (Figure 8). Converting from single pulse to 3-pulse burst reduces the ablation rate as plotted in Figure 8 at P_{av} = 260W and P_{av} = 990W. As seen in Figure 2b, the ablation efficiency is constant between single pulse and burst mode when φ_0 < 3.5J/cm^2 without the generation of additional thermal effect as confirmed by Raman spectroscopy (Figure 9). Therefore, this reduction of ablation rate is only the consequence of processing at a lower fluence per pulse.

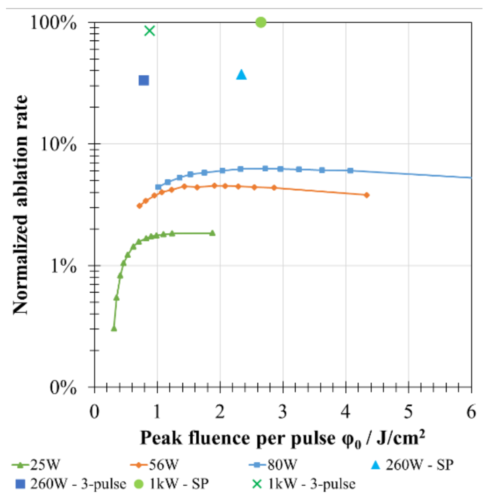

Figure 9. Normalized ablation rate as a function of the peak fluence per pulse φ_0 for different average powers P_{av}. Results are displayed at single pulse and 3-pulse burst when P_{av} > 260W

Concerning the other grades, no improvement of the initial surface roughness is achieved after the optimization trials of the laser ablation process at P_{av} = 260W and P_{av} =990kW. As already experienced in previously published work[2], laser polishing coarser PCD grades is more challenging than fine grades. The cavities formed by the spallation of the diamond grains do not allow to perform a reduction of the initial roughness of medium and coarse grade surfaces at high power.

4. CONCLUSION

A 1kW femtosecond laser system (λ =1030nm and τ = 500fs) is first tested to investigate the variation of surface roughness S_a as a function of the fluence per pulse φ_0 for a wide range of values from φ_0 = 0.88J/cm^2 to 50.42J/cm^2 at single pulse. A burst mode is also experimented to test the effects of the number of pulses in a burst on the surface roughness compared to single pulse processing. This investigation demonstrates the existence of several ablation regimes for each PCD grade and the specific evolution of the surface roughness S_a upon laser ablation at single pulse and burst mode processing per PCD grade:

- For fine PCD grade, two regimes take place starting with the ablation of cobalt followed by the ablation of diamond at higher fluences. The S_a reduces with the addition of pulses per burst: by 10% from single to 5-pulse. The repetition of pulses in a burst on the PCD surface causes incubation effects which allows processing of the diamond at a lower fluence, and therefore reduces the residual heat and the related thermal damage.
- For medium PCD grade, the ablation of diamond results in the spallation of diamond grains after the ablation of cobalt at lower fluence. The diamond ablation proceeds in two distinct regimes where the size and number of the cavities (< 5µm) left from the expulsion of the diamond grains increase from one regime to another of higher fluence. Even though incubation effects occur with the burst mode, the reduction of residual heat does not improve surface roughness of medium grade compared to single pulse. The high thermal conductivity of medium grade (higher than fine grade) allows the evacuation of the residual heat into the bulk of the material and the minimization of localized thermal effects at single pulse already.
- For coarse PCD grade, the ablation process at single pulse follows the one described for fine grade with two regimes; however, the addition of pulses in a burst leads to an enhancement of the spallation of diamond grains and clearly results in three regimes at 7-pulse burst like for medium grades. Considering the high fluence threshold (higher than finer grades), the burst mode allows a more efficient ablation of the large PCD grains (~25um) thanks to incubation effects and results in a S_a lower by 55% than achieved at single pulse.

The laser ablation process is then scaled up to an average power P_{av} = 990kW. A polishing laser operation is finally developed for fine grade surfaces which is capable of:

- A reduction by 14% of the initial surface S_a
- A 140 times increase of volume removal rate compared to a traditional mechanical process (70 times increase compared to previous study at P_{av} = 80W).
- With no phase transformation of the diamond structure

However, the cavities formed by the spallation of the diamond grains on coarser PCD grade surfaces prevent a reduction of their initial roughness during the laser polishing trials at P_{av} =1kW as far as now.

The laser polishing of fine grades can be optimized further on fine grade surfaces with a 5-purst and potentially a higher number of pulses per burst in order to achieve a higher Sa reduction than 14%. Regarding coarser grades, the formation of cavities must be prevented to allow an efficient polishing of the initial surface.

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